High-Resolution Ocean and Atmosphere pCO_2
Time-Series Measurements

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1. Project Summary

Fossil fuel carbon sources and the growth of atmospheric carbon dioxide (CO_2) are reasonably well known based on economic reconstructions and atmospheric monitoring. Global carbon budgets suggest that over decadal timescales the ocean is absorbing, on average, approximately one third of the CO_2 released from human activity. However, the inter-annual variability in the ocean uptake and variability in the basic regional patterns of the air-sea CO_2 fluxes are poorly known at this time.

Ocean carbon measurements have shown significant biogeochemical variability over a wide range of timescales from sub-diurnal to decadal periods. In situ measurements are also providing a growing body of evidence that episodic phenomena are extremely important causes of variability in CO_2 and related biogeochemical properties. Time-series records are essential for characterizing the natural variability and secular trends in the ocean carbon cycle and for determining the physical and biological mechanisms controlling the system. The biological and chemical responses to natural perturbations (e.g., El Niño/Southern Oscillation, dust deposition events) are particularly important with regard to evaluating potential responses to anthropogenic forcing and for evaluating the prognostic models used in future climate projections. Ship-based time-series measurements are impractical for routinely measuring variability over intervals from a week to a month, they cannot be made during storms or high-sea conditions, and they are too expensive for remote locations. Instrumental advances over the past 15 years have led to autonomous moorings capable of sampling properties of chemical, biological, and physical interest with resolutions as good as a minute and duty cycles of a year or more. Although these new technologies are still underutilized, they have been identified as a critical component of the global ocean observing system for climate.

The primary mission of this project is to evaluate the variability in air-sea CO_2 fluxes by conducting high resolution time-series measurements of atmospheric boundary layer and surface ocean CO_2 partial pressure (pCO_2). The Moored Autonomous pCO_2 ($MAPCO_2$) system collects CO_2 data from surface seawater and marine boundary air every three hours for up to a year at a time before they need servicing. Daily summary files of the measurements are transmitted back

to PMEL where the data are examined and plots of the results are posted to the web in near-real time. In FY2011, PMEL maintained twelve sites initiated in previous years. With twelve moorings currently fitted with pCO_2 systems, we are currently at 24% completion of the open ocean moored CO_2 program goal.
A global network of surface ocean and atmospheric CO_2 observations will make a substantial contribution to the production of seasonal CO_2 flux maps for the global oceans. The long-term goal of this program is to populate the network of Ocean Sustained Interdisciplinary Time-series Environment observation System (OceanSITES; www.oceansites.org) so that CO_2 fluxes will become a standard part of the global flux mooring network. This effort has been endorsed by the OceanSITES science team. The moored CO_2 program directly addresses key element (7) Ocean Carbon Network, as outlined in the Program Plan, but also provides a value added component to elements (3) Tropical Moored Buoys and (6) Ocean Reference Stations.

Users of these data include scientists investigating high frequency variability in surface ocean properties, data synthesis groups developing air-sea CO_2 flux maps (e.g. Takahashi climatology, Surface Ocean CO_2 Atlas [SOCAT], NOAA flux maps) and researchers studying ocean acidification. The data are currently being used to evaluate regional and global carbon models. Several of the near real-time buoy displays are used in web pages and graphics used to inform the general public and policy makers about the ocean carbon system. Additional information can be found at: www.pmel.noaa.gov/co2/story/Buoys+and+Autonomous+Systems.

2. Scientific Accomplishments

In FY2011, PMEL maintained twelve sites initiated in previous years. There were a total of 13 servicing visits to these sites in FY2011. Each servicing required the preparation of replacement systems so the $MAPCO_2$ equipment could be swapped to maintain a continuous data stream. In some cases new pCO_2 systems were needed to replace older less reliable systems or systems that were lost at sea during the year.

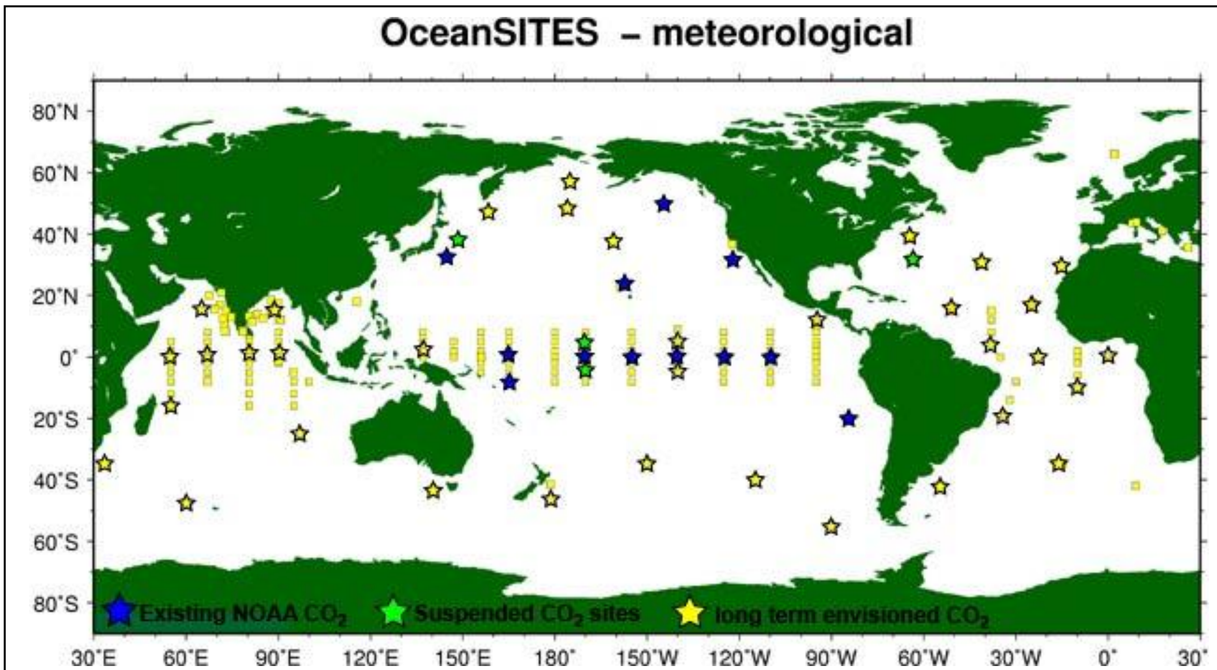

Figure 1. Map of the OceanSITES meteorological moorings with stars indicating locations of moored pCO_2 systems currently planned and deployed as part of this program.

The long term goal of this program is to populate 50 OceanSITES flux reference moorings with pCO_2 systems (Figure 1). With twelve moorings currently fitted with pCO_2 systems, we are currently at 24% completion of the open ocean moored CO_2 program goal.

Instrument/Platform Operations in FY2011

Here we summarize the deployment schedules and instrument performance over the last year. Systems are grouped into four categories. Seven systems are located in the equatorial Pacific on the TAO moorings operated by the National Data Buoy Center (NDBC). Two systems are on Woods Hole buoys operated by Bob Weller. One system is located in the California Current operated by Uwe Send of Scripps. Two systems are in high-latitude buoys operated by Meghan Cronin (PMEL) as part of an OCO funded Ocean Climate Stations project, one located off of Japan and one at Station Papa. At the end of each summary, we give two sets of percent data returns. The first is the Mooring Operational Time (MOT), which is the percent of time that the mooring was deployed, not-vandalized and anchored on station. Lifetime MOT is calculated from the first time that the $MAPCO_2$ system was deployed on that platform. The second is the $MAPCO_2$ data return, which only reports times as operational when a system returned both good quality seawater and atmospheric values.

Equatorial Pacific on TAO Moorings:

110°W, 0° - At the beginning of FY2011, the $MAPCO_2$ system at this site was lost at sea. A new system was deployed in August. The system operated well until late September when it started transmitting uncontrollably many times per day. In order to avoid large transmission fees, the sim card in the system was deactivated and thus the system has not been able to transmit data back to the lab. There is a chance that there is good data stored in the $MAPCO_2$ memory card, which we will recover once the system is replaced in January.
Mooring Operational Time (MOT) in FY2011: 19%, Lifetime: 42%
Percent of MOT that $MAPCO_2$ returned data in FY2011: 82%, Lifetime: 91%

125°W, 0° - The $MAPCO_2$ system was functioning well at the start of FY2010. Unfortunately, the buoy went adrift on November 6th. The buoy and system were recovered and a new system was deployed on December 7th. The system functioned well for the remainder of the year.
Mooring Operational Time (MOT) in FY2011: 52%, Lifetime: 83%
Percent of MOT that $MAPCO_2$ returned data in FY2011: 100%, Lifetime: 84%

140°W, 0° - At the start of FY2011, the system was not operational due to vandalism. The system was replaced in late November 2010 and functioned well for the remainder of the fiscal year.
Mooring Operational Time (MOT) in FY2011: 100%, Lifetime: 85%
Percent of MOT that $MAPCO_2$ returned data in FY2011: 85%, Lifetime: 84%

155°W, 0° - On September 9, 2010 the buoy was boarded to make repairs to other instrumentation. During the repair it seems that the equilibrator assembly was inadvertently damaged and seawater pCO_2 data were lost for the remainder of the deployment. The $MAPCO_2$ system was replaced in late November 2010 and functioned well for the remainder of FY2011.
Mooring Operational Time (MOT) in FY2011: 100%, Lifetime: 100%

Percent of MOT that $MAPCO_2$ returned data in FY2011: 68%, Lifetime: 80%

170°W, 0° - The $MAPCO_2$ system at this location was operational for all of FY2011.
Mooring Operational Time (MOT) in FY2011: 100%, Lifetime: 93%
Percent of MOT that $MAPCO_2$ returned data in FY2011: 100%, Lifetime: 93%

165°E, 0° - At the start of FY2011, the $MAPCO_2$ system at this site was operating without a high gas standard due to a leak. Through post-processing, the data collected after the standard ran out will be recalculated with reasonable accuracy. A full system replacement was completed in March and the system was operational for the remainder of the year.
Mooring Operational Time (MOT) in FY2011: 100%, Lifetime: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2011: 100%, Lifetime: 100%

165°E, 8°S – At the start of the year, the system at this site had been deployed for 16 months due to the reduction of ship sea days. The battery which was designed for the 12 month deployment ran out after 15 months and did not collect data during the final month of deployment. The system was replaced in October 2010 with a larger battery pack. It operated well for the entire year.
Mooring Operational Time (MOT) in FY2011: 100%, Lifetime: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2011: 92%, Lifetime: 96%

WHOI Moorings

WHOI Hawaii Ocean Time-series Station (WHOTS) (157°W, 22°N) –The $MAPCO_2$ system at this location was operational until a new system was deployed July 2011. After comparing the data from 3 other sources, it became obvious that the seawater values from the new system were implausibly high. The cause of this error is still under investigation and will be carefully studied when the site is serviced in May 2012.
Mooring Operational Time (MOT) in FY2011: 100%, Lifetime: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2011: 79%, Lifetime: 84%

Stratus (19.7°W, 85.5°N) – The buoy at this site broke free of its mooring on July 7, 2010. The buoy and CO_2 system were recovered by a vessel of opportunity, but a replacement buoy did not get deployed until April 2011. The system at this site was fully operational for the time it was in the water.
Mooring Operational Time (MOT) in FY2011: 49%, Lifetime: 85%
Percent of MOT that $MAPCO_2$ returned data in FY2011: 100%, Lifetime: 100%

Scripps Moorings

California Current #1 (CCE1) (122.5°W, 33.5°N) – At the start of this year, the system was functioning well. Unfortunately the buoy broke free on October 19th. The buoy and $MAPCO_2$ system were recovered, but were not redeployed until March 2011. The $MAPCO_2$ system operated well the entire time the buoy was deployed.
Mooring Operational Time (MOT) in FY2011: 63%, Lifetime: 77%
Percent of MOT that $MAPCO_2$ returned data in FY2011: 100%, Lifetime: 100%

Ocean Climate Stations Moorings

Kuroshio Extension Observatory (144.5°E, 32.3°N) – The $MAPCO_2$ system deployed at the KEO site was operational until June 2011 when the seawater readings became suspect. The system was replaced in November 2011 and it is again fully operational. The past year was the fourth successful deployment at this location after moving to the high latitude

buoy (HLB) in September 2007. Lifetime calculations below only consider deployments in a high latitude buoy.
Mooring Operational Time (MOT) in FY2011: 100%, Lifetime: 100%
Percent of MOT that MAPCO$_2$ returned data in FY2011: 73%, Lifetime: 91%

Papa (145°W, 50°N) – The MAPCO$_2$ system at this site was fully operational for all of FY2011.
Mooring Operational Time (MOT) in FY2011: 100%, Lifetime: 100%
Percent of MOT that MAPCO$_2$ returned data in FY2011: 100%, Lifetime: 100%

Quality Assurance and System Improvements

Logistically, the MAPCO$_2$ program continues to be economical in its operations. The pCO$_2$ systems are mounted in buoys that are deployed from ships contracted through other projects. Currently all of our deployments are in conjunction with another project that is covering the buoy deployment and maintenance costs and has already allocated ship time. The pCO$_2$ systems are typically sent out on a cruise and are set up and deployed by a member of the scientific party as an ancillary task. This arrangement requires about 4 hours for setup and then approximately 10 additional man hours during the cruise. To keep expenses down we generally request that someone already involved in the cruise be trained to deploy the systems so we do not have to pay to send our people to sea for every deployment. During every deployment, someone from the PMEL CO$_2$ group stands by to remotely turn on the system after the buoy is deployed and to ensure that is running properly before the ship leaves the site. In addition to turning the system on and off, all parameters can now be changed remotely to optimize data collection. This approach requires that the systems be very robust and easy to setup.

FY2011 is the first year that we have not released a new version of firmware or made any hardware changes for the MAPCO$_2$ system. This fact demonstrates that the MAPCO$_2$ system has become very stable, dependable and robust. With this stability has come savings in engineering development time and technician testing time. The latest version of MAPCO$_2$ firmware, released in August of 2010, collects and transmits data from several auxiliary sensors including the SAMI2 – pH system and a SBE-16V2 (a temperature and conductivity sensor that can host up to 3 other sensors). Additionally, the MAPCO$_2$ system can remotely start and stop the SBE-16V2 which will keep the pumps from burning out if they are accidently left to run on land. These additional capabilities allow the user to gain a more complete understanding of the surface water carbon system and to alleviate the need for PMEL personnel to be on site during deployments.

We are very close to adding a water level sensor for the MAPCO$_2$ equilibrator. This sensor will give us detailed information about where our equilibrator is floating in times of high seas and strong currents. On a rare occasion in the past, the equilibrator has been jammed above the waterline as a result of vandalism, fishing or biofouling. We believe that this could be the cause behind the questionable values noted in the previous section. This will be a relatively inexpensive, but important diagnostic tool for remotely confirming to proper operation of the floating equilibrator, currently the most likely source of failure in the system.

In FY2011, the Moored CO$_2$ program continued the great strides made in FY2009 and FY2010 to make the MAPCO$_2$ technology more accessible to the public, more reliable and more accurate by transferring the MAPCO$_2$ technology from PMEL to Battelle Memorial Institute. We continue to provide the firmware for the Battelle systems and also provide technical and advisory assistance to ensure that they are providing the best the MAPCO_2 systems to the public. Additionally, although on the surface the Battelle systems appear to cost more than producing them in-house, we are saving a great deal of engineering and technician time by not having to assemble the systems ourselves.

Throughout the year, many inter-comparisons were run between the PMEL MAPCO_2 systems, the underway pCO_2 systems and the Battelle built systems both in the laboratory and in the field on various ships. The MAPCO_2 system has consistently compared favorably with the shipboard systems over a wide range of conditions. With the help of our colleagues at Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), we are currently in the process of upgrading our lab testing environment. We are building a tool that will gather the data from all the systems testing in the lab into one program. It will collect data from underway pCO_2 systems, MAPCO_2 systems and temperature and conductivity instruments. This tool will process data immediately and display everything on one screen enabling lab technicians to see in real time the precision and accuracy of the systems being tested.

Data Processing

In FY2011, we made significant advancements in data processing and access. Up until FY2010, our data processing was only semi-automated using Excel spreadsheets and VBA macros. This was manageable when we only had a few systems in the water, but as the network has grown data management has become a significant challenge. In FY2010 and FY2011, we invested in a professional programmer at PMEL to develop a data management system that automatically receives and processes the raw Iridium data, prepares the diagnostic information for easy evaluation, posts updated data plots on the web, and helps us to keep track of inventory and deployment schedules. The data management program is being modeled after the TAO data management system. The system is now fully in place and managing CO_2 data from our moorings. This has significantly improved the efficiency of the moored CO_2 program.

Each of the 12 currently deployed MAPCO_2 systems transmits a daily summary file of data to PMEL via Iridium satellite. The diagnostic information (battery condition, flow rates, etc.) is examined to ensure that the systems are still functioning properly. The raw CO_2 measurements are converted to a common scale (CO_2 mole fraction in dry air) and graphed on a new website that is updated daily (www.pmel.noaa.gov/co2/map). Launched in February 2011, the PMEL Carbon Group website (www.pmel.noaa.gov/co2) is completely revised and enhanced. The website includes detailed information on ocean carbon research, a description of each CO_2 mooring with links to our partners' websites, and a more user-friendly interface. For example, Figure 2 shows a plot of recent data from the Papa mooring displayed on the new Google Earth data portal. This portal allows users to use a mapping interface to view near real time CO_2 data around the world. The raw summary data are currently stored at PMEL and are available from C. Sabine upon request.

Once the systems are recovered and returned to the laboratory, the full raw data set can be analyzed. We use a system for processing the moored pCO_2 data utilizing semi-automated quality control procedures developed within our group. Based on the calibration information as well as other diagnostic measurements for each identified point relative to the surrounding

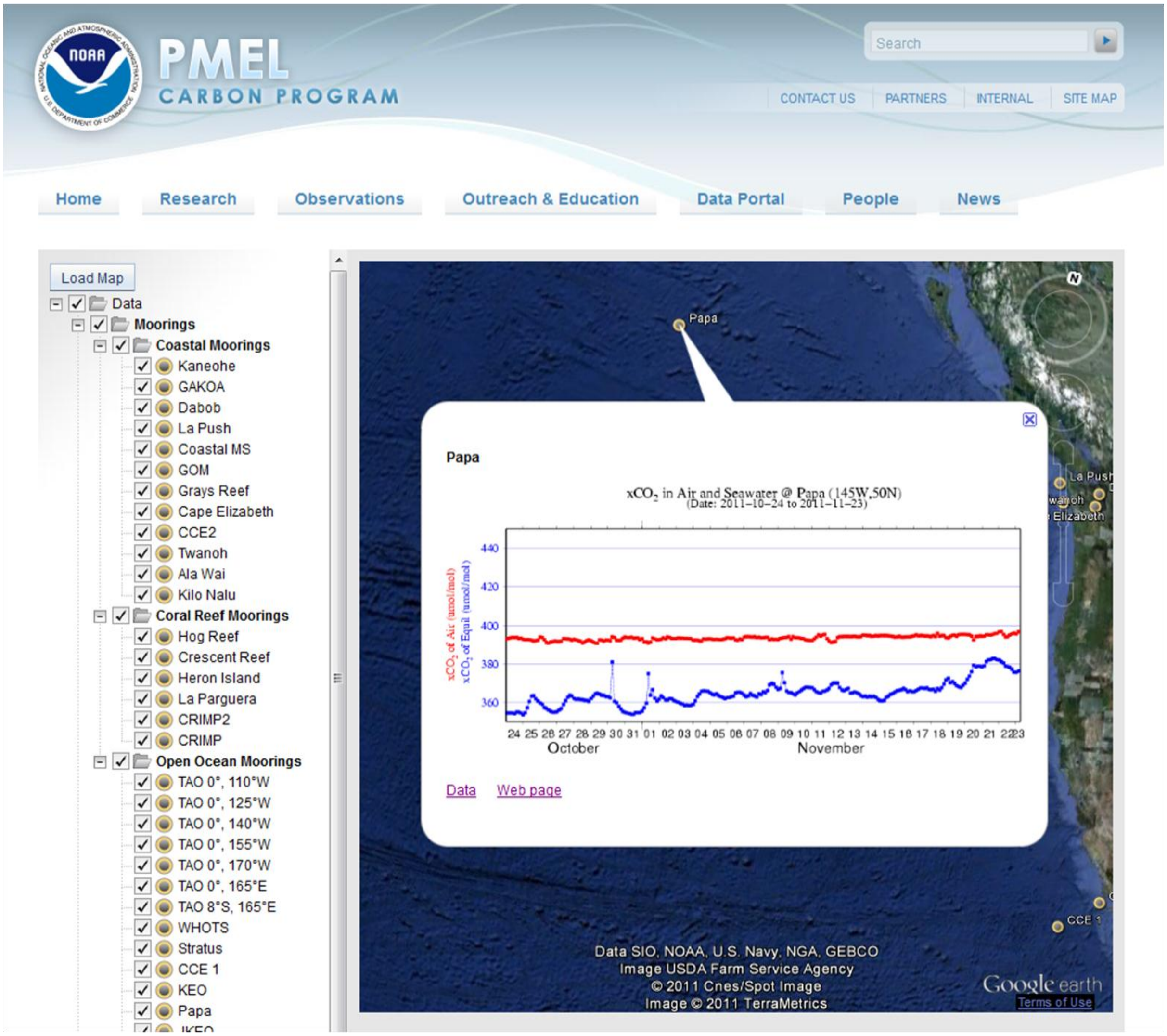

Figure 2. Time series plot of raw transmitted surface water CO_2 mole fraction (blue) and atmospheric CO_2 mole fraction (red) on the Papa mooring. The new Google interface allows the user to zoom into the region of interest and click on the mooring to view the entire time series or the most recent near real time data.

points, the data point may be flagged as questionable or bad. Typically less than 1% of the data are flagged. To finalize a dataset, the seawater values are compared to any underway pCO_2 data that are available and the atmospheric values are compared to Marine Boundary Layer (MBL) atmospheric CO_2 concentrations provided by NOAA's GLOBALVIEW-CO_2 network. Based on these comparisons and various diagnostics, the entire data set (air and water values) may be adjusted to match these higher accuracy measurements. Typically these adjustments are less than a couple of parts per million. The data are then merged with sea-surface temperature and salinity data collected on the same buoy (typically by other groups).

As all data become available, final calibrated values are archived at the Carbon Dioxide Information Analysis Center (CDIAC) and the National Oceanographic Data Center (NODC) for public data access and archiving on a yearly basis. We have made significant progress in finalizing recovered CO_2 mooring. In FY2011, we finalized CO_2 data from 8 active mooring sites (WHOTS, KEO, Papa, TAO125W, TAO140W0N, 170W0N, Stratus, and CCE1) and 3 inactive sites (MOSEAN, JKEO, and BATS). The cumulative number of years of data processed and finalized in FY2011 was 34. As of the time of the submission of this report, most of the CO_2 moorings recovered in FY2010 have been finalized and submitted to CDIAC for public release. We are actively processing the few remaining datasets and will have them submitted shortly.

Analysis and Research Highlights

The moored CO_2 network is providing a wealth of information about the time and space scales of variability in surface water pCO_2 and air-sea fluxes that we are only just beginning to examine. The value of time series lies in their continued data collection. The primary deliverable from this project is the collection of another year's worth of high frequency, high quality surface carbon data. These data are essential for understanding how the ocean carbon system is changing with time. Datasets comparable to the ones we are collecting do not exist for ocean carbon. We are now monitoring variability at an unprecedented 12 open ocean sites. Every site so far has shown different trends in variability. These data are necessary to generate air-sea flux estimates and accurate assessments of the net annual gas exchange, which serve the ocean observing system for climate program deliverable to better understand the extent to which the ocean sequesters CO_2 and how cycling among ocean-land-atmosphere carbon reservoirs varies on seasonal-to-decadal time scales. Multi-year records also tell us about inter-annual variability at these sites and ultimately will resolve the secular trends resulting from rising atmospheric CO_2.

For example, we have been measuring CO_2 in Hawaiian waters since 2004, first on the MOSEAN H-A mooring through July 2007 and since then, on the WHOI Hawaii Ocean Time-series Station (WHOTS) mooring. Figure 3 shows an increasing trend in ocean and atmosphere

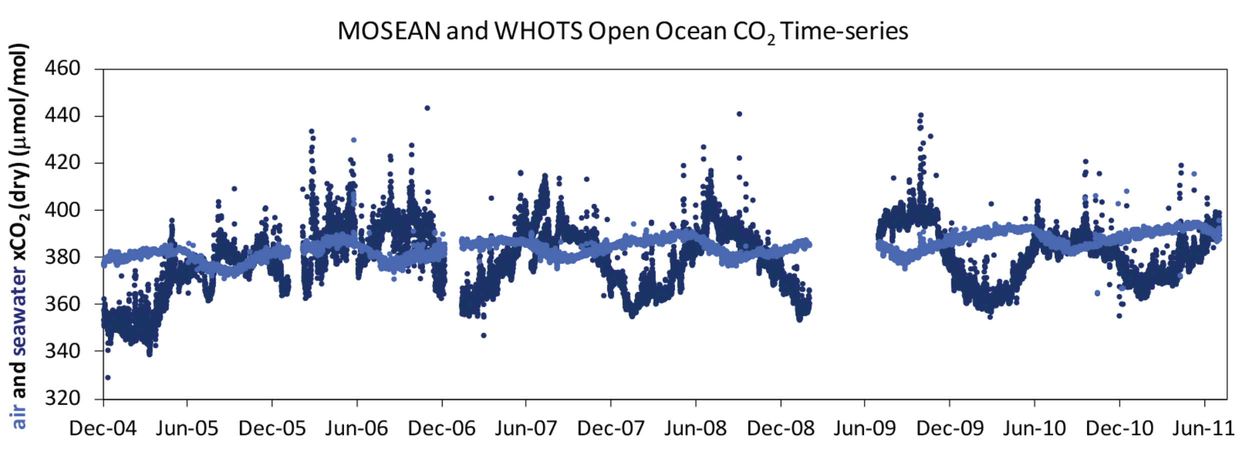

Figure 3. Time series plot of atmospheric CO_2 (light blue) and surface seawater CO_2 (dark blue) at the open ocean time-series off Hawaii (at the now inactive MOSEAN site from 2004-2007 and the active time-series location at WHOTS from 2007-present). From: Sabine et al. 2011 World Climate Research Program (WCRP) poster.

CO_2 over the 7 year time-series. Seasonal fluctuations are also apparent in both seawater and air (e.g., low seawater CO_2 in the winter and high seawater CO_2 in the summer).

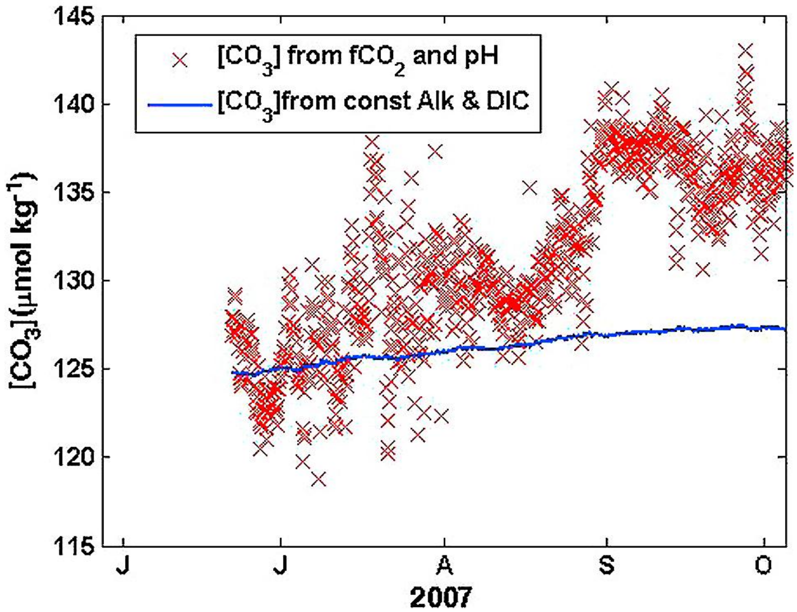

Figure 4. Carbonate ion (CO_3) concentrations (red) calculated using CO_2, pH, temperature, and salinity measurements from the Station Papa mooring during 2007. For comparison, [CO_3] was also calculated using constant alkalinity and dissolved inorganic carbon (DIC) values (blue line). Figure from Emerson et al. 2011.

Mooring CO_2 measurements were also central to a paper recently published in *Global Biogeochemical Cycles*. Emerson et al. (2011) used the Papa mooring CO_2 and pH time-series from 2007 to estimate the rate of calcium carbonate ($CaCO_3$) formation, which is critical for improving our understanding of the biological pump and the importance of carbon export in the North Pacific. The observed increase in carbonate concentrations (red symbols in Figure 4) during summer months demonstrate the formation of $CaCO_3$ due to some combination of biological processes and gas exchange. This data was used to validate a mass balance model that suggests the rate of $CaCO_3$ production is about half the total organic carbon production in the summer. This time-series will be critical to understanding how the biological pump, carbon flux, and the rate of $CaCO_3$ production by phytoplankton may change as anthropogenic CO_2 increases in the surface ocean. This type of research also contributes to a better understanding of the extent to which the ocean sequesters CO_2 and how cycling among ocean-land-atmosphere carbon reservoirs varies on seasonal-to-decadal time scales, a main deliverable of the ocean observing system for climate.

2.1. Outreach and Education

Dr. Sabine, the PI of this project, presented scientific research from the moored CO_2 program to the public in several forums including local grade schools, open public lectures (both in the US and abroad), public "webinars" (seminar broadcast as streaming video onto the web) and laboratory tours. He gave numerous press interviews and was quoted in printed and online media, radio, and television.

As part of this program we transferred the PMEL moored pCO_2 system to private industry (Battelle Memorial Institute) so that the larger scientific community will have access to these moored systems. We have interacted with numerous laboratories around the US and internationally to explain how the $MAPCO_2$ systems work and the infrastructure requirement needed to deploy them, including hands on training exercises with students and researchers at Friday Harbor Labs, WA and in Venice Italy (sponsored by the Alliance for Coastal Technologies [www.act-us.info]). As a result of this outreach as well as the consistently good performance of the system in inter-comparison studies, the $MAPCO_2$ system is considered the "gold standard" for moored CO_2 systems.

In FY2011, we completely revised and updated the PMEL Carbon Group website (www.pmel.noaa.gov/co2). Between the launch in February 2011 and the end of FY2011, the website had over 75,000 unique visitors. The new website includes detailed background information on ocean carbon uptake (www.pmel.noaa.gov/co2/story/Ocean+Carbon+Uptake) and how our research contributes to a better understanding of the role of the ocean in the global carbon cycle. We also include a detailed description of each CO_2 mooring (www.pmel.noaa.gov/co2/story/Buoys+and+Autonomous+Systems) and a new Google Earth data portal (www.pmel.noaa.gov/co2/map). Other education and outreach highlights include our news page (www.pmel.noaa.gov/co2/news), our archive of multi-media stories (www.pmel.noaa.gov/co2/story/Multi-media), and our educational tools on ocean acidification and the carbon cycle (www.pmel.noaa.gov/co2/story/Education).

3. Publications and Reports

3.1. Publications by Principal Investigators

Bond, N.A., M.F. Cronin, C. Sabine, Y. Kawai, H. Ichikawa, P. Freitag, and K. Ronnholm (2011): Upper-ocean response to Typhoon Choi-Wan as measured by the Kuroshio Extension Observatory (KEO) mooring. J. Geophys. Res., 116, C02031, doi: 10.1029/2010JC006548, 8 pp.

Borges, A.V., S.R. Alin, F.P. Chavez, P. Vlahos, K.S. Johnson, J.T. Holt, W.M. Balch, N. Bates, R. Brainard, W.-J. Cai, C.T.A. Chen, K. Currie, M. Dai, M. Degrandpre, B. Delille, A. Dickson, W. Evans, R.A. Feely, G.E. Friederich, G.-C. Gong, B. Hales, N. Hardman-Mountford, J. Hendee, J.M. Hernandez-Ayon, M. Hood, E. Huertas, D. Hydes, D. Ianson, E. Krasakopoulou, E. Litt, A. Luchetta, J. Mathis, W.R. McGillis, A. Murata, J. Newton, J. Olafsson, A. Omar, F.F. Perez, C. Sabine, J.E. Salisbury, R. Salm, V.V.S.S. Sarma, B. Schneider, M. Sigler, H. Thomas, D. Turk, D. Vandemark, R. Wanninkhof, and B. Ward (2010): A global sea surface carbon observing system: inorganic and organic carbon dynamics in coastal oceans. In *Proceedings of the "OceanObs'09: Sustained Ocean Observations and Information for Society" Conference (Vol. 2)*, Venice, Italy, 21–25 September 2009, Hall, J., D.E. Harrison, and D. Stammer, Eds., ESA Publication WPP-306, doi: 10.5270/OceanObs09.cwp.07.

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Fassbender, A.J., C.L. Sabine, R.A. Feely, C. Langdon, and C.W. Mordy (2011): Inorganic carbon dynamics during northern California coastal upwelling. Cont. Shelf Res., 31(11), doi: 10.1016/j.csr.2011.04.006, 1180–1192.

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Hamme, R.C., P.W. Webley, W.R. Crawford, F.A. Whitney, M.D. DeGrandpre, S.R. Emerson, C.C. Eriksen, K.E. Giesbrecht, J.F.R. Gower, M.T. Kavanaugh, M.A. Peña, C.L. Sabine, S.D. Batten, L.A. Coogan, D.S. Grundle, and D. Lockwood, 2010. Volcanic ash fuels anomalous plankton bloom in subarctic Northeast Pacific. Geophys. Res. Lett., 37, L19604, doi: 10.1029/2010GL044629.

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Park, G.-H., Wanninkhof, R., Doney, S. C., Takahashi, T., Lee, K., Feely, R. A., Sabine, C., Triñanes, J., and Lima, I., 2010. Variability of global net sea-air CO_2 fluxes over the last three decades using empirical relationships: Tellus, v. 62B, p. 352-368

Sabine, C.L., Feely, R.A., Wanninkhof, R., Takahashi, T., Khatiwala, S., Park, G.-H., 2011. Global oceans: The global ocean carbon cycle. In: Blunden, J., Arndt, D.S., Baringer, M.O. (Eds.), In State of the Climate in 2010, Bulletin of the American Meteorological Society,, pp. 92(96):S100-S105), doi:110.1175/1520-0477-1192.1176.S1171.

3.2. Other Relevant Publications

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